Surface Imaging of W Ursae Majoris Contact Binaries

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1. Introduction

The W UMa type binaries are contact systems formed by two solar type components and are probably the most enigmatic group among close interacting binaries.

The eclipsing W UMa systems show a light curve with minima of about the same depth, therefore the effective temperatures of the two components should be almost the same, in spite of the fact that they always are dwarf stars of different mass. The difference $\Delta T_e = T_{e,1} - T_{e,2}$, the index 1 indicating the primary (i.e. the more massive) component, is not more than some hundred degrees, even for mass ratios of only some tenths, and it can even be negative, with a smaller component hotter than the more massive one (again by some hundred degrees). The physical explanation of these well-established small temperature differences is one of the challenges, until now without a completely satisfactory answer, of close binary astrophysics. Binnendijk was probably the first to realize this paradoxical situation and we may call this unexplained but well-known property the *Binnendijk paradox*.

This peculiar temperature difference, which is certainly related to the production and to the transfer of energy between the two components, is not the only enigma of W UMa binaries. Already in the forties Kuiper (1941) pointed out that contact binaries filling the inner Roche lobe should have a ratio of the volumes determined by the Roche geometry. This predicts, in a very large range of mass ratios, $V_2/V_1 = q^{1.35}$. On the other hand the ZAMS relation requires $V_2/V_1 = q^{\alpha}$ with $\alpha = 2.0 \pm 0.1$. The two relations can be simultaneously fulfilled only for q = 1, but all the known W UMa systems have mass ratios smaller than one. This is the so-called *Kuiper paradox*.

Both paradoxes teach us that the components of W UMa binaries have temperatures and radii that strongly deviate from the predictions for single stars evolving between ZAMS and TAMS, at least for one of the components.

The difficulties in formulating a consistent scenario are enormous: for instance the solution of the Binnendijk paradox requires the modelling of the energy transfer through a thin common envelope. This cannot be performed without taking into account strong Coriolis forces and unknown magnetic fields between tidally interacting components.

The problem deriving from the Roche lobe filling of the two components, which is confirmed by the light-curve solutions obtained by means of the Wilson-Devinney procedure (see next section), is also without clear solutions. The major difficulty is, in this case, to predict how the volumes of the two stars will react in the case of mass transfer. This mass transfer is a direct consequence of the angular momentum loss experienced by the system by virtue of magnetically trapped ionized stellar winds and controlled by the dynamo of the convective zone. The angular momentum loss mechanism, first formulated by Schatzman (1962) for solar-type single stars, is also a fundamental ingredient in the process leading to the formation of solar-type contact binaries from detached systems. By virtue of spin-orbit coupling, in fact, it will produce a shrinking of the orbit and finally transform the

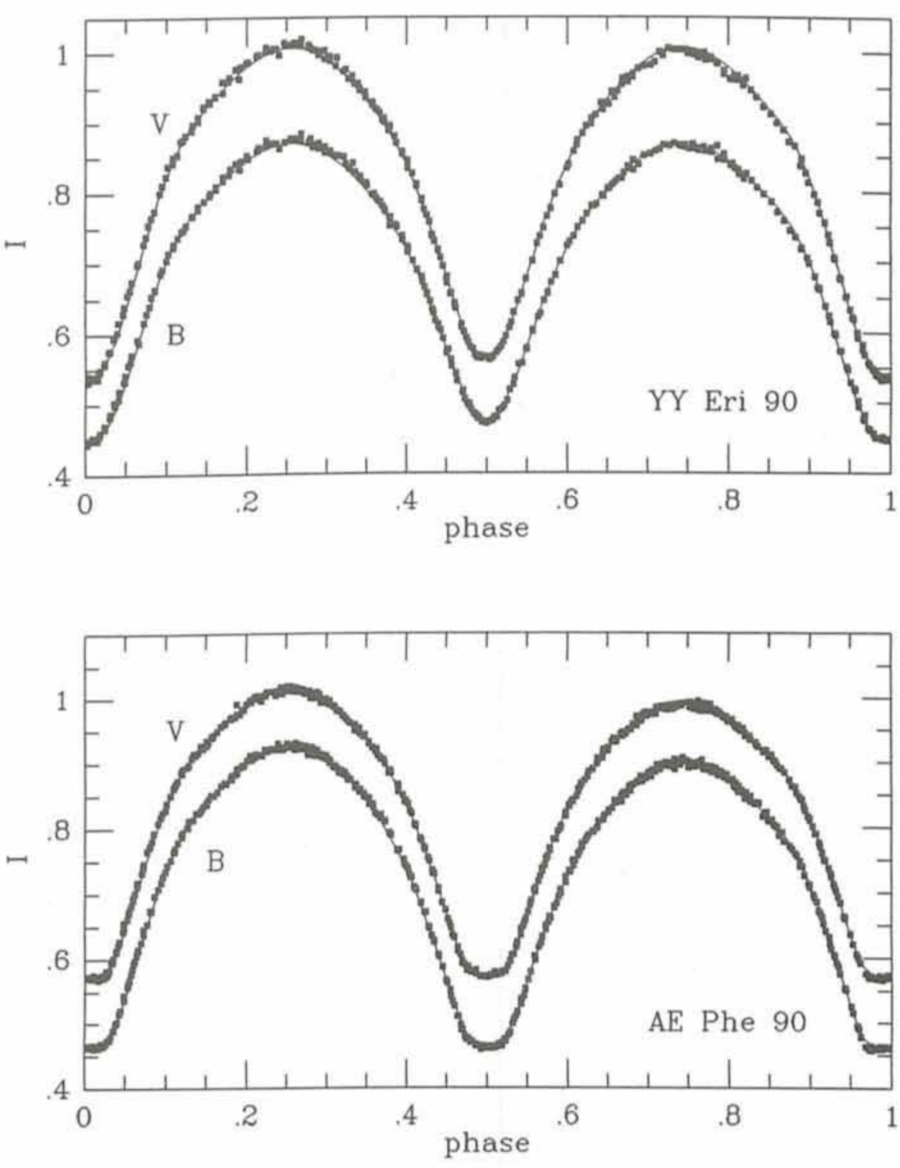
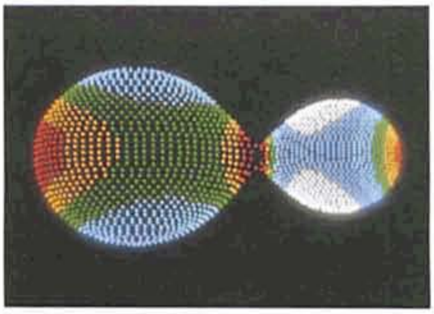


Figure 1: *B and V light curves of YY Eri and AE Phe. The continuous lines (often hidden by the observed points) are the light-curve solutions.*



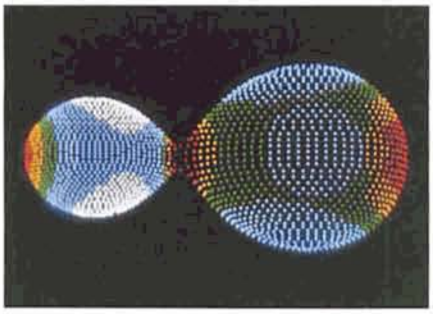


Figure 2(a): *Effective temperature distribution, from the light-curve solution, for the surface of AE Phe visible at phase 0.25. Effective temperature goes from 5020 to 6130 K. The colour scale is shown in Figure 3.* (b) *Effective temperature distribution of AE Phe at phase 0.75.*

detached system into a contact binary (Van 't Veer, 1975; Vilhu, 1982).

There is no doubt about the presence of even strong magnetic fields in these stars: we have direct evidence from the light curve perturbations, which are attributed to dark or hot spots, and from indirect clues, i.e. the excited chromospheres and coronae.

In principle dark spots on the surface of the primary component can explain the inversion of the temperature difference, but this type of model would require the permanent presence of extended dark spots on the back hemisphere of the primary, a thesis difficult to support. However, we know that bright and/or dark spots with shorter lifetimes (say, ~ some years) are present from the perturbations of the light curves. All W UMa binaries that have been observed for some years show light-curve variations. These can cover every phase domain, but they are best visible during the maxima and minima and may consist of a change of height and depth of these extremes. It is also possible that the phase of one or more of these extremes is shifted.

Even if the signatures of surface inhomogeneities clearly appear in the light curves, the photometry alone cannot unambiguously determine the type of the perturbations (hot or dark), and their location, so that one cannot distinguish between the effects of the interaction between the two components (energy and mass exchange producing hot spots) and those of magnetic activity. The best way to solve the problem is a Doppler Imaging analysis of high-dispersion spectra which yields a brightness surface map of the system. This is the reason why we proposed a programme of simultaneous spectroscopic and photometric observations of two suitable southern W UMa systems, AE Phe and YY Eri. The programme, the method of data analysis and the (provisional) results are described in the following sections.

2. The Observations

2.1 The photometry

We had six observing nights in November 1989 and seven more one year later. The stars were simultaneously observed with the CAT telescope, equipped with the CES spectrograph, short camera and CCD and with the ESO 50-cm telescope (with its single-channel photometer, the EMI 9789Q photomultiplier and the standard B, V filters). Unfortunately in the 1989 season three nights out of six were non-photometric, AE Phe was observed for two nights and YY Eri only for one. As a consequence we got only incomplete light curves. The 1990 season, however, was completely successful: we had 100% of photometric nights.

The first thing we found out was that the primary minima were in both cases delayed by about half an hour with respect to the ephemerides given by Gronbeck (1976, for AE Phe) and Breger (1981, for YY Eri). This means a phase shift of respectively 0.060 and 0.077. The fact is not surprising given the shortness of the periods (both around 0.3 days) and the long time passed since the last ephemerides.

From the individual observations, (Fig. 1) we derived the mean point light curves which were solved by means of the Wilson and Devinney code, in the last standard distributed version (Wilson, 1979) which includes a partial treatment of dark/hot spots.

The code uses a physical model of the contact binary based on the Roche lobe configuration. The surface brightness distribution of the common envelope deviates from a uniform distribution because of gravity darkening effect (von Zeipel, 1929; Lucy, 1968), which makes the poles brighter than the back and the equators of the components, and because of the mutual reflection of the irradiated light (brightening the facing hemispheres). The model is used to compute a theoretical light curve as function of a number of physical parameters: the wavelength, the mass ratio,

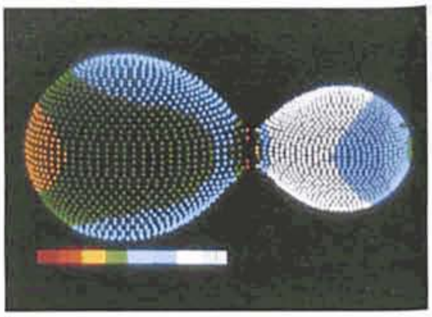


Figure 3: *Effective temperature distribution from the light-curve solution of YY Eri at phase 0.25 (the same, in this case, as the distribution at phase 0.75). Effective temperature goes from 5050 to 5630 K. The colour scale goes from dark red to white with increasing T_e.*

the inclination, the filling factor (which express the degree of filling of the space between the internal and external Roche critical surfaces), the difference between the effective temperatures, the luminosity ratio and, finally, three coefficients taking into account the limb darkening, the gravity darkening and the reflection effect.

An elementary linearized least square algorithm, with derivatives computed by finite differences approximation, provides the differential corrections to a starting set of adjustable parameters. By means of an iterative procedure the method converges to the best set of parameters, i.e. what is commonly called the light-curve solution. This numerical procedure is often hindered by strong correlations among the adjustable parameters, which demands a decrease of their number, by using theoretical or estimated values (this is often the case for the values of the gravity darkening, the limb darkening and the reflection coefficients), and the use of the method of subsets (Wilson and Biermann, 1976).

The WD code is in general successful in finding morphologically excellent and physically meaningful solutions (one should perhaps mention that the most common difficulty with it is the non-unicity, at least with respect to some parameters, and not the lack of solutions). This is true at least as long as the curves do not show perturbations asymmetric with respect to the minima. In the last case it is still possible to model the common envelope introducing hot or dark spots, even if, for reasons connected to the determinacy of the solutions, the spot parameters are not adjusted. However, in spite of this constraint, the solution with spots is very often non unique: the photometry alone does not contain enough information to discriminate between a hot spot of given location and size and a dark spot elsewhere (see for instance Maceroni, Van 't Veer and Van Hamme, 1990. Maceroni and Van 't Veer, 1990). A long continuous series of (multi-wavelength) observations of the same system can help to overcome the problem, but repeated homogeneous observations are not available for most of the known systems. This explains the importance of using simultaneously the photometry and the high-dispersion spectroscopy, which yields independent information about the location of the perturbed regions.

Figures 2 and 3 show the geometrical configuration corresponding to the simultaneous (in B and V) solutions of Figure 1, together with the spot location and the effective temperature distribution. Both systems show asymmetric perturbations of the light curves; the most evident feature of this effect is that the maximum following primary minimum (max I) is brighter than the other (max II).

In the case of AE Phe we modelled this feature by means of a hotter spotted region reaching maximum visibility at phase 0.25. This choice was suggested by the first indications from the spectroscopic data reduction, showing the presence of extra emission in H_α at max I.

With a similar procedure we have found the solution of YY Eri. In its case we find a region of enhanced brightness on the connecting neck.

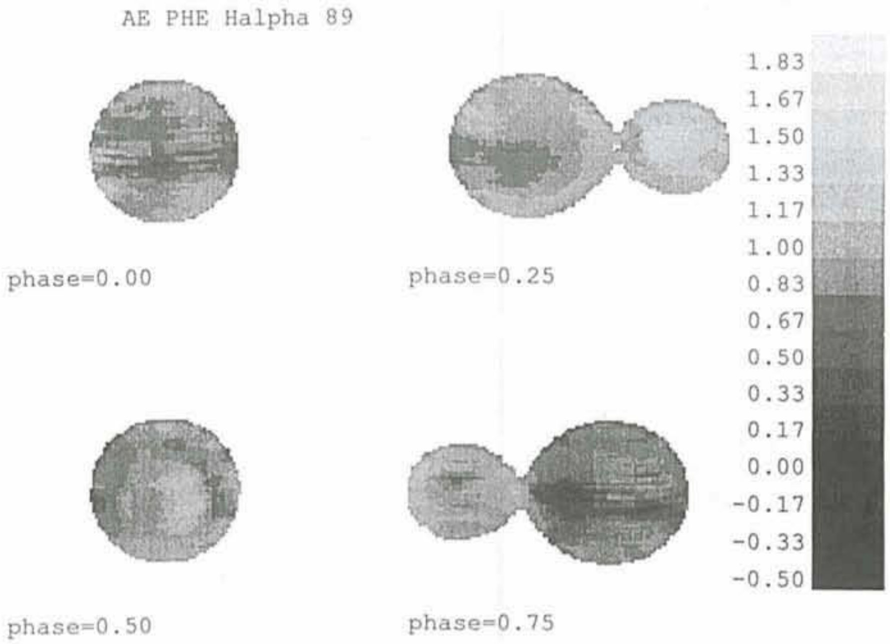


Figure 4: *Doppler images of AE Phe. The mapped quantity, S, is the scale factor of the solar H_α equivalent width (see text). S = 0 means that no line is present, S < 0 means emission line. Qualitatively the relation with the temperature is in the sense that dark areas correspond to lower T_e.*

2.2 The high-dispersion spectroscopy

The Doppler Imaging method is based on the fact that a dark starspot produces a bright bump in a rotationally broadened absorption line profile. This can be intuitively understood considering what happens to the line profile if we insert a completely dark (and small) spot on the surface of a rotating star. The effect will be the disappearance of the contribution of the now darkened region from the profile. This consists of a narrow absorption feature, displaced from the line centre by the roation, and of a contribution to the continuum at all the other wavelengths of the broadened line. The final algebra gives that at the wavelengths corresponding to the velocity shift of the spot the flux decreases less than at the others, thus producing the bright bump. During a stellar rotation the bump moves across the profile in a way connected to the position on the surface. It is therefore clear that one can, in principle, extract information on the surface brightness distribution from a set of Doppler-broadened profiles taken at different phases.

In practice, however, the "inverse problem" of reconstructing a brightness surface map from the profiles is rather difficult, being an "ill-posed" problem. This means that one can find many spot distributions producing the same effect on the line profiles. As a consequence one has to apply further constraints (usually in the form of a regularizing function which chooses the simplest of all possible maps). A detailed description of the method can be found in Vogt and Penrod (1983) and in Piskunow, Tuominen and Vilhu (1990).

The application of the Doppler imaging technique to contact binaries is not at all straightforward. First of all, severe constraints limit the observable sample. The most serious difficulty arises from the short periods (and hence high rotational velocities) coupled to low luminosities of these systems. The exposure times should be a compromise between the need of high S/N ratio, necessary to resolve weak features in a heavily broadened profile, and that of covering no more than 0.05 in phase (which means exposures shorter than 20 minutes). With CAT telescope and CES spectrograph at a resolution of about 60,000 we were obliged to select relatively bright systems ($m_v \sim 8$) and strong lines: the Balmer H_α line at 6563 Å and the Sodium D1 and D2 at 5890/95 Å. The disadvantage of the strong lines, compared to the weak Fe lines commonly used in Doppler imaging, is that their interpretation is more difficult, because of contamination by the chromospheric layers. However, they are also sensitive to photospheric spots and one should also say that enhanced chromospheres are probably connected with spots.

Additional difficulties are due to the fact the modelling of a contact system is much more difficult than that of a single star (or a detached binary): the unperturbed photosphere (i.e. without spots) is not uniformly bright and, moreover, one has to take into account the surface shape and the corresponding radial velocity distributions.

The surface images of Figures 4 and 5 are the preliminary results of the analysis of the H_α profiles. In the first step of the treatment we assumed that the H_α equivalent width, W, could be expressed as $W = S * W_\odot$, being $W_\odot$ the solar value and S only function of the position on the surface. Furthermore, we also assumed that the profile shape is the same as that of the sun, being again simply scaled by a factor S. This is only a first-order approximation, the next step will be the computation of the local line profile by means of model atmospheres.

The local profiles were broadened and weighted using the local radial velocities and outgoing fluxes in the observer direction computed by means of the WD code.

The maps of Figures 4 and 5 show with different grey tones the resulting S distribution. The transformation of the S scale into a temperature scale, directly comparable with Figures 2 and 3, requires the dependence of W on the effective temperature and gravity, and

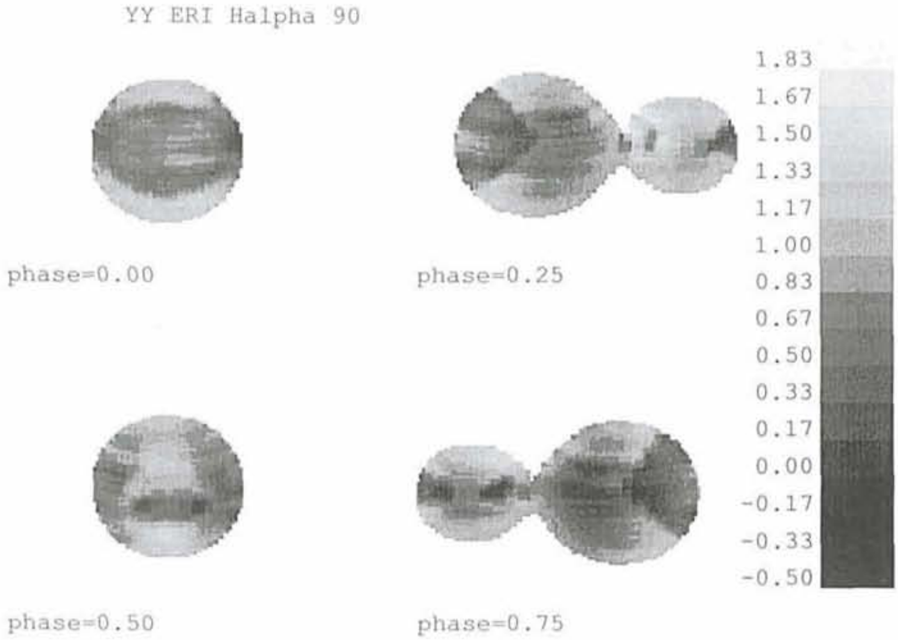


Figure 5: *Doppler imaging surface maps of YY Eri.*

hence the use of the appropriate model atmospheres. However, on a more qualitative ground, we know that darker tones correspond to colder areas; from a first rough estimate S = 1.83 corresponds to 350 K above the mean and S = 0.5 to 400 K below.

The similarity between the photometric and spectroscopic maps is evident, at least with reference to the distribution on a large scale. In both cases the fitting of the data requires a smooth non-uniform temperature distribution with the stellar poles hotter than the backs and the equators. Therefore we can say that the models from photometry and spectroscopy are at this level fully consistent. On the other hand, the detailed analysis of the surface features requires a less simple treatment, that we are still developing. Even in absence of spots we have a T distribution over the surface, which implies a variation of the line equivalent width and affects the reference values of S (i.e. the value corresponding to the unperturbed photosphere). To disentangle this effect from the actual brightness variation we are undertaking the computation of local profiles by means of model atmospheres.

3. Discussion and Conclusions

The Doppler imaging was already successfully applied to less rapidly rotating objects by other people, but as far as we know never to W UMa stars. With this experience we intended to examine if it is also possible to obtain new information about these capricious, rapidly rotating objects. The reason for this approach was clear. From the measurements of visible light curve, UV and X we know that these binaries are seats of magnetic activity. Furthermore, it is generally believed that high AML is controlling the evolution of these binaries towards the single-star stage, involving mass transport from the secondary to the primary component. Nobody presently understands how this mass transport takes place and how it is interacting with magnetic, tidal and Coriolis forces. It can be hoped that from a better survey of the brightness inhomogeneities on the surface, a better insight in the origin of these inhomogeneities, and related large-scale motions, can be obtained.

Our first results are encouraging for a further development of the application of this method. However, we feel that the next step will most probably require the use of the 3.6-m telescope, to have the possibility of enlarging the observable sample and of analysing less strong (and simpler) spectral lines.

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Are the Nebulae Around R Coronae Borealis Stars Evolution or Ejection Related?

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The R Coronae Borealis (R CrB) stars are a rare group of cool hydrogen-deficient supergiants whose light variations are characterized by dramatic fading of up to visual mag. 9 and a slow recovery to maximum. Spectroscopically they appear to be extremely hydrogen-deficient and carbon rich. Their evolutionary history has been the source of much controversy. Mixing scenarios for single AGB stars (Schönberner, 1986) have been unable to reconcile the observed photospheric abundances with model predictions. Recently two rather exotic scenarios have emerged that address this problem:

- *The last thermal pulse scenario* (Renzini, 1979, 1981 and Iben et al., 1983). Calculations have shown that if a white dwarf suffers a thermal pulse it may be intense enough to re-ignite a helium-burning shell sending the star towards the AGB for a second time ('Born again' AGB star). The R CrB stars are suspected to be at this stage. This process is accompanied by large-scale mixing of the photosphere. Although the computational work is great it does appear that the time spent at the AGB is